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Analyses of phase change materials' efficiency in warm-summer humid continental climate conditions

J Ratnieks¹, S Gendelis¹, A Jakovics¹ and D Bajare²

¹University of Latvia, Laboratory for mathematical modeling of environmental and technological processes, Zellu str. 23, Riga, Latvia

²Riga Technical University, Faculty of Civil Engineering, Azenes str. 16, Riga, Latvia

E-mail: janis.ratnieks@fizmati.lv

Abstract. The usage of phase change materials (PCMs) is a way to store excess energy produced during the hot time of the day and release it during the night thereby reducing the overheating problem. While, in Latvian climate conditions overheating is not a big issue in traditional buildings since it happens only a couple of weeks per year air conditioners must still be installed to maintain thermal comfort. The need for cooling in recently built office buildings with large window area can increase significantly. It is therefore of great interest if the thermal comfort conditions can be maintained by PCMs alone or with reduced maximum power of installed cooling systems. Our initial studies show that if the test building is well-insulated (necessary to reduce heat loss in winter), phase change material is not able to solidify fast enough during the relatively short night time. To further investigate the problem various experimental setups with two different phase change materials were installed in test buildings. Experimental results are compared with numerical modelling made in software *COMSOL Multiphysics*. The effectiveness of PCM using different situations is widely analysed.

1. Introduction

In order to reduce cooling energy consumption, PCMs are being used as a passive system for temperature condition stabilization in the room. This kind of system saves energy that would be used for cooling and more important, in Latvian climate conditions, could even save the costs of installing air cooling devices. A lot of papers have dealt with phase change materials being installed in a testing environment and have achieved results where the effect of PCM is shown compared with the similar environment without PCM [1] and [2]. Other papers deal with thermal comfort condition improvement in the living environment [3]. The modelling is also done to some extent, like in [4]. An issue that occurs for PCMs is that passive systems do not solidify fast enough during the night when the temperature is lower. High air exchange rates are used in [2] and [4] to ensure that solidification occurs during the night.

The aim of the study is to evaluate how many cycles can PCM effectively use in hotter periods as a passive system in warm-summer humid continental climate conditions. To achieve the goal, two different PCMs are installed in different test buildings that are located in Riga, Latvia. The testing ground consists of five buildings, with the ones without PCM used for comparison. Data from summer seasons of years 2015 and 2016 are taken and analyzed. Typical overheating cycles are selected and by employing numerical model the phase change phenomena are studied



in greater detail. The testing ground, sensors used and measurement periods are described in section 2.

The experimental data are analyzed in section 3 where some already known as well as expected patterns are observed. This leads to the next task of evaluating the time a PCM is working. As there is no good way of telling whether the inside of the material is in molten state, a mathematical model is used that is described in section 4.

2. Experimental setup

2.1. Testing environment

The test buildings are localized in the urban environment, under natural conditions in Riga, Latvia, characterized by warm-summer humid continental climate. The average heating period is 203 days and average annual temperature is 6.2 °C. Therefore buildings with good thermal insulation are necessary. While the summer season is short, the overheating issues are still present as shown later [5] [6] [7].

Each experimental stand is a free-standing building, placed in equal relation to the sun and the surrounding shading objects. They have 9 m² floor area and 3 m ceiling height with a window on the south facade and a front door on the north facade see figure 1. Each building is placed on pillars and has no direct contact with the ground. The U-values of wall assemblies are calculated approximately as 0.15 [$\frac{W}{m^2 \cdot K}$]. The basic materials used for the ventilated facade exterior wall



Figure 1. Testing ground, located in Riga, Latvia with sensor positions on the left.

construction are:

- 1) perforated ceramic blocks (440 mm) with flexible stone wool insulation outside (type CER);
- 2) aerated concrete blocks (375 mm) with flexible stone wool layer outside (type AER);
- 3) modular plywood panels with flexible stone wool filling (200 mm) and fibrolite (70 mm) inside (type PLY);
- 4) laminated beams (200 mm) with flexible stone wool insulation layer and wood paneling inside (type LOG). [6], [7]

The thermal masses of each building's wall envelope are calculated as [$\frac{MJ}{K \cdot m^2}$] and are given in table 1. The calculated heat capacity of PCM latent heat is taken from the manufacturers' data. Heating/cooling systems, windows, doors, as well as roof and floor constructions are made equal with the same spatial direction so the wall assemblies could be compared.

The PCMs installed on the inner walls of test buildings can be seen in figure 2 and their properties in table 2. The placement of PCMs have been researched previously and it is shown in [8] and [9] that the inner surface placement is not the best option, however due to the fact that testing environment already existed there was no option to change the placement. The work of

Table 1. Thermal mass of each construction.

wall assembly	LOG	CER	PLY	AER
thermal mass (w/o pcm), $\frac{MJ}{K \cdot m^2}$	0.19	0.37	0.11	0.18
PCM latent heat, $\frac{MJ}{m^2}$	1.45	0.52	0	0
PCM present	+	+	-	-

**Figure 2.** Phase change materials installed: LOG building on the left and CER building on the right

[9] is purely experimental and does not take into account that there is a direct thermal radiation through the windows that can change the actual performance.

Table 2. Phase change materials' properties.

	LOG	CER	
Latent heat	200	121	$\frac{kJ}{kg}$
Thermal conductivity	0.2	0.14..0.18	$\frac{W}{m \cdot K}$
Density	860	810	$\frac{kg}{m^3}$
Melting temperature	25	21.6	$^{\circ}C$

2.2. Data acquisition system and sensors

To monitor ambient temperature data a meteorological station located on the top of AER building collects temperature, humidity, precipitation and other information. In each test building more than 20 sensors collect data on temperature, humidity, solar radiation etc. The indoor temperature is calculated as average of 5 sensors that are placed in the middle of horizontal plane at various heights (0.1, 0.6, 1.1, 1.7 and 1.9 m above the floor). Data are collected every minute and once per day sent to the server. The data experimentally acquired are averaged over an hour and used as an input for the numerical model described in later chapters. More on monitoring system can be read in [10] and [11].

3. Data analysis

Two different time periods were experimented with during summer 2016 . The first was from 1 May to 1 July where no cooling was provided and the mechanical ventilation was switched off. And the second period started 1 July where cooling and mechanical ventilation was switched on. The measured temperatures are shown in figure 3. The outside weather conditions are given as MET.

It can be seen that during period one CER building has lower temperature values for hot sub-periods and higher temperature values for cooler sub-periods. This can be attributed to thermal mass that is almost twice as big as LOG and AER buildings have and more than three times the PLY building. It is, therefore, difficult to correctly evaluate the effect of PCM. In figure

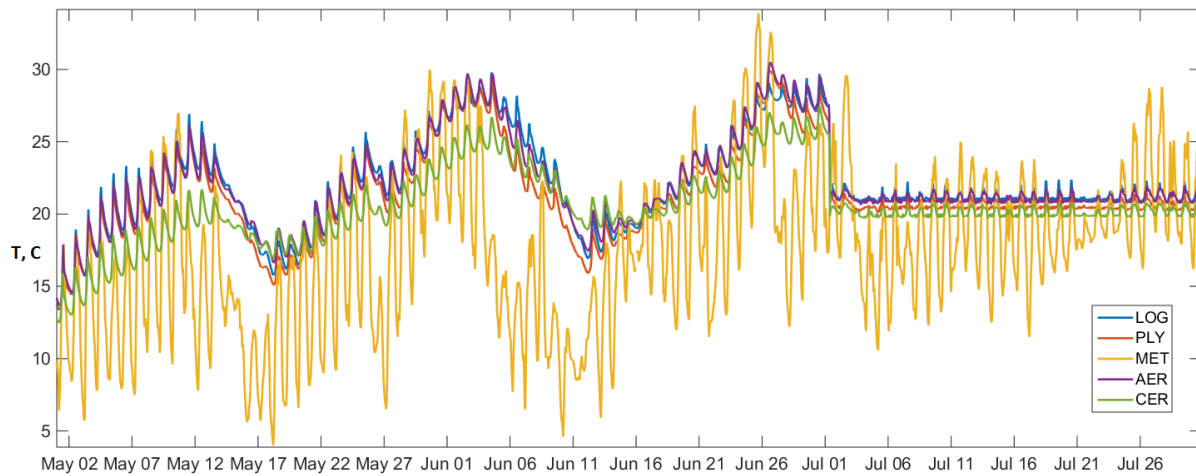


Figure 3. Inner temperatures in buildings and outside temperature during the summer 2016.

4, it is shown that at the phase change temperature of CER building's PCM the behaviour of daily cycle slightly changes. This can be seen in more detail in the subsequent numerical model section. PLY, LOG and AER buildings the behaviour is quite similar except for PLY that is cooling down faster than LOG and AER. During the brief moment from June 3rd until June 10th the AER building shows faster decrease than LOG building and this period lies in the phase change temperature of LOG PCM's phase change temperature. For the second period cooling temperature was set to 21 °C and the air exchange of $n = 0.45[h^{-1}]$ [12]. The set temperature for cooling was below the phase change temperature of any of two PCMs installed (see tables 1 and 2) and therefore no heat is saved due to PCMs. Temperature control gives a clue that there is a temperature level difference between test buildings. This is believed to be due to temperature sensor offset between cooling units. The total energy consumption is given for all the buildings. Also, the average temperatures during the cooling period are shown in table 3.

Table 3. Average temperatures, inner heat gains and cooling energy for test buildings during second (cooling) period from June 1st until August 31st.

	LOG	PLY	CER	AER
$Q_{cooling}, kWh$	31.3	33.9	35.5	35.2
Q_{inner}, kWh	20.6	22.8	25.5	46.5
$T_{avg}, ^\circ C$	21.2	20.6	20.1	21.0

The inner sources are due to sensors, data loggers and other consumers found in buildings. The AER test building has higher energy gains from inner sources because the meteorological station is placed there that consumes extra power. The energy required is lowest for LOG building but this is compensated by the fact that it has the highest average inside temperature during the second period. To fully interpret data and see which construction consumes the lowest amount of energy an energy balance calculation must be made. However it's obvious that the difference will be marginal as it is now.

A 2015 summer season was also considered in this study. The only difference was that the outside weather was colder on average and the mechanical ventilation was turned on. These data are later used in section 4 where they are compared with those of the year 2016.

4. Numerical model

A 1D numerical model is set up in *COMSOL Multiphysics* with a single material wall of the same thermal mass and effective thermal conductivity as the CER building has. The thermal mass in this context is to be understood as the amount of heat in J a square meter of wall assembly can store per one K temperature difference. A heat transfer equation is solved that is well known and therefore not given in this paper. There are third type boundary conditions towards inner and outer environment with heat transfer coefficients being $7.7[\frac{W}{m^2.K}]$ for inner environment and $25[\frac{W}{m^2.K}]$ for outside environment. The time dependent temperature is taken from experimental data and shown in figure 4 as red and green lines for outside and blue lines for inner temperature. The end of summer 2015 is cut off in figure 4 as these results are not presented here.

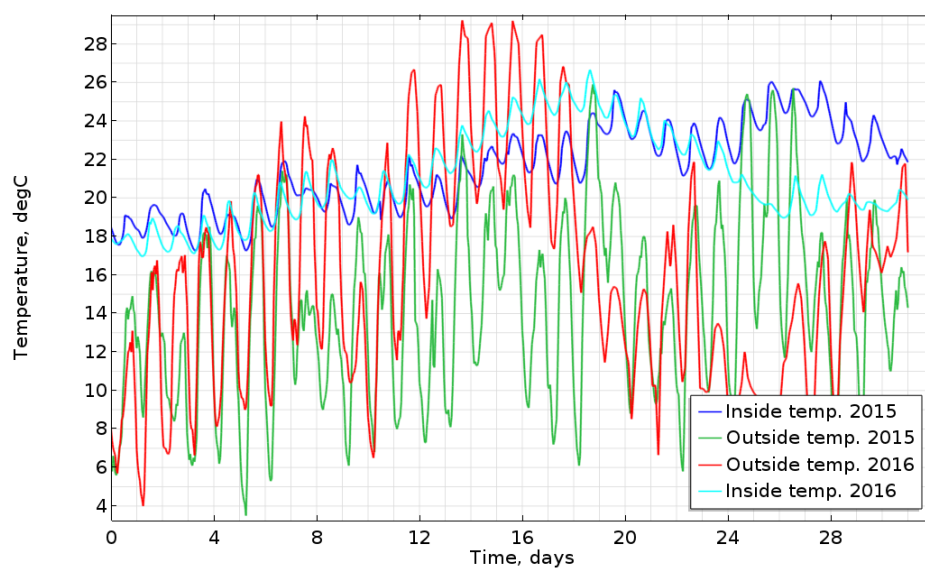


Figure 4. Temperature dependence on time for mathematical model.

The first calculation was done from 17 May 2016 to 17 June 2016 and the second from 19 May 2015 to 01 July 2015. The PCM was considered in a solid state initially. Calculations were started a week before the first melting in order to get realistic temperature distribution as the initial conditions depicted constant temperatures.

5. Results

The results are best viewed as a phase diagram where time is shown on X axes and phase - either solid or liquid - is shown on Y axes where unity represents liquid state and zero represents solid state, see figures 5 and 7. Temperature inside, on the surface, and between the PCM and wall is shown in figures 6 and 8. The experimental data for second period - cooling below phase change temperature - shows that there is a temperature measurement offset from one air conditioning unit to another. This must be considered in future experiments when they include cooling above the phase change temperature.

Qualitatively looking at the experimental data it is hard to notice the difference of temperature regimes for LOG and AER buildings despite the fact that they have similar constructions' thermal mass but one has PCM while the other doesn't. This gives a rise to doubt if the PCMs are of any use. The cooling consumption is shown in table 3. It has been measured previously that mechanical ventilation alone needs approximately 40 W that adds up for 59.2 kWh just for

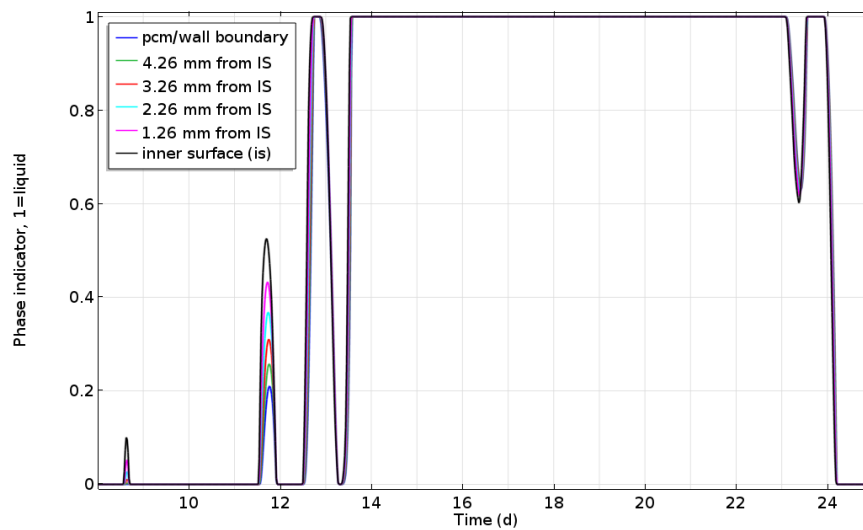


Figure 5. PCM phase dependence on time from mathematical model for overheating cycle in 2016; inner surface being PCM and inner air boundary.

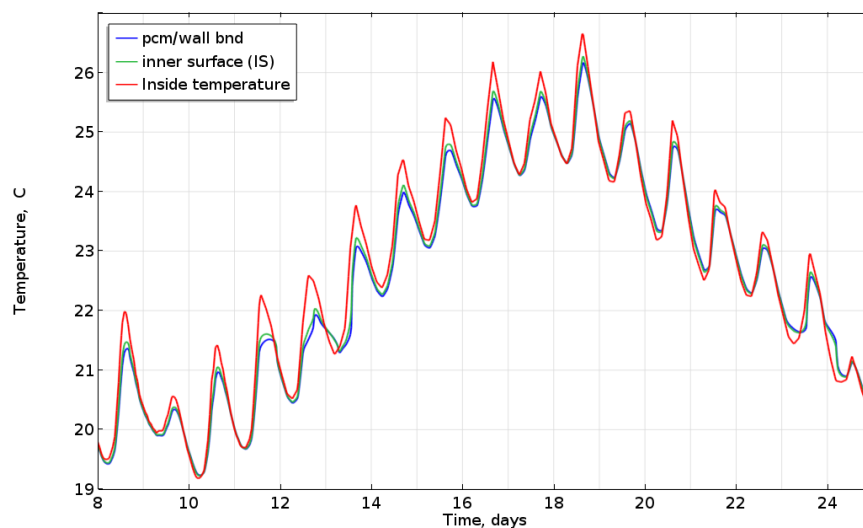


Figure 6. Temperature dependence on time from mathematical model for overheating cycle in 2016.

ventilation in the given period. The cooling energy required therefore is comparable to energy needed for ventilation system to work and negligible compared to heating energy consumption during the winter. In figure 4, it is clearly seen that average temperature is higher in summer 2016 and the peak values are also higher during that period. The hot period (when outside temperature is higher than phase change temperature) starts on day 11 and mathematical model shows that until end of day 13 all the PCM have molten down, see the phase indicator diagram figure 5. After this melting for remaining of hot period, although outside temperature goes below phase change temperature the solidification does not happen and overheating occur.

For year 2015 the ventilation is $n = 0.45[h^{-1}]$ and the outside temperature on average is lower. In this case the PCM melts and solidifies from day 13 until day 18 when the inside temperature gets too high for solidification to occur again, see figure 7. For a given period the effect of the

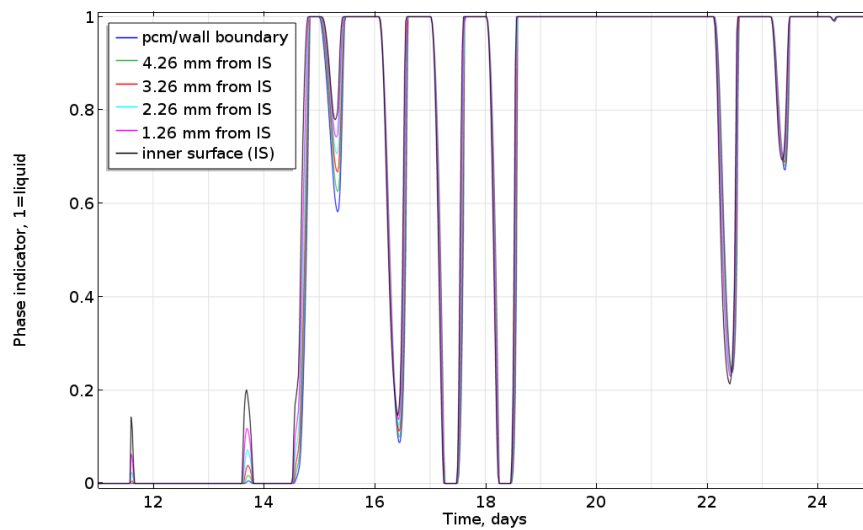


Figure 7. Temperature dependance on time for mathematical model for overheating cycle in 2015; inner surface being PCM and inner air boundary.

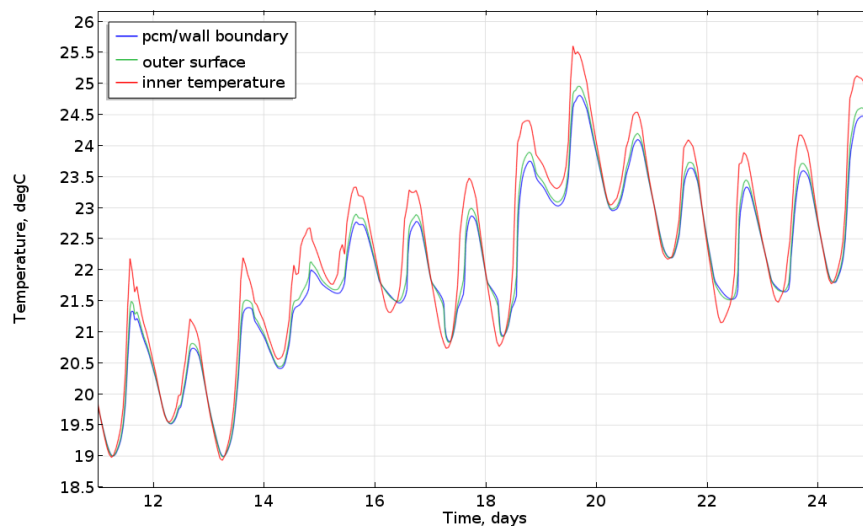


Figure 8. Temperature dependance on time for mathematical model for overheating cycle in 2015.

PCM can be clearly seen by looking at the figure 8 where inside temperature is not rising above 23 °C till day 18 and then after the PCM have molten down, it rise rapidly. In warm summer humid continental climate conditions the buildings must be built with good thermal insulation - $U=0.15 \frac{W}{m^2 \cdot K}$. This effect can be seen in figures 5 and 7 at days 11 and 15, respectively. In case where the temperature rises, melting happens more on the inner surface where more than half of the material undergoes phase change (it is assumed that phase change occur over interval of 0.5 °C) while at the wall/PCM interface only 20% has undergone phase change. The reverse is true for solidifying where wall/PCM boundary can't solidify while the PCM closer to inside of room haven't solidified.

6. Discussion

The cooling energy demand in Latvian climate conditions is low and almost negligible compared with other devices. The PCM usage therefore is not justified in sense of cooling energy saving. However taking into account short summer seasons with typical temperature peak periods the PCM could be used as a passive system that can completely eliminate the need for air conditioning device. In this sense the use of PCMs could be justified and further studies on the subject are recommended.

Despite CER building having lower overall PCM's latent heat, the effect is qualitatively seen, compared to other buildings. In the case of LOG building, the temperature level is the same as in similar buildings without PCMs, the only difference being at the end of hot period when temperatures are decreasing.

7. Conclusion

Qualitatively it can be seen for the CER case that PCMs reduce peak temperatures during hotter periods. The effect, if any, is barely seen in LOG building despite higher latent heat being released. Numerical model shows that the peak temperature reduction only happens during first few days of longer high temperature periods and for periods long enough or hot enough the overheating is not eliminated. A larger amount of PCM could be used to overcome those periods. Additional studies are suggested regarding: validation of mathematical model. Additional temperature sensors will be installed in cooling season 2017; viability of PCM usage in Latvian climate conditions are proposed; an increase of mechanical air exchange during the night is proposed to achieve solidification during the night.

Acknowledgments

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